

High energy cosmic rays, gamma rays and neutrinos from AGN

Yukio Tomozawa

*Michigan Center for Theoretical Physics, Randall Laboratory of Physics,
University of Michigan, Ann Arbor, MI. 48109-1040*

(Dated: February 5, 2008)

The author reviews a model for the emission of high energy cosmic rays, gamma-rays and neutrinos from AGN (Active Galactic Nuclei) that he has proposed since 1985. Further discussion of the knee energy phenomenon of the cosmic ray energy spectrum requires the existence of a heavy particle with mass in the knee energy range. A possible method of detecting such a particle in the Pierre Auger Project is suggested. Also presented is a relation between the spectra of neutrinos and gamma-rays emitted from AGN. This relation can be tested by high energy neutrino detectors such as ICECUBE, the Mediterranean Sea Detector and possibly by the Pierre Auger Project.

PACS numbers: 04.70.-s, 95.85.Pw, 95.85.Ry, 98.54.Cm

I. INTRODUCTION

High energy gamma rays from AGN have been reported by the EGRET detector at the Compton Observatory [1] and by Cerenkov Detectors[2]. More recently a possible correlation between high energy cosmic rays and the distribution of AGN locations has been reported[3]. In this respect, the author had proposed a model for the emission of high energy particles from AGN since 1985, and the implications of the knee energy in high energy cosmic ray spectrum had been clarified. In this report, the author summarizes the proposed model and further explores the implication of the knee energy. As an additional prediction of the model, the ratio of neutrinos and gamma rays from AGN is computed.

II. SUMMARY OF THE MODEL

In a series of articles[4]-[12], the author has presented a model for the emission of high energy particles from AGN. The following is a summary of the model.

1) Quantum effects on gravity yield repulsive forces at short distances[4],[6].

2) The collapse of black holes results in explosive bounce back motion with the emission of high energy particles.

3) Consideration of the Penrose diagram eliminates the horizon problem for black holes[7]. Black holes are not black anymore.

4) The knee energy for high energy cosmic rays can be understood as a split between a radiation-dominated region and a matter dominated region, not unlike that in the expansion of the universe. (See page 10 of the lecture notes[4]-[6].)

5) Neutrinos and gamma rays as well as cosmic rays should have the same spectral index from each AGN. They should have the knee energy phenomenon, a break in the energy spectral index, similar to that for the cosmic ray energy spectrum.

6) The recent announcement by Hawking rescinding an earlier claim about information paradox[13] is consistent

with this model.

The discussion of the knee energy in the model is recapitulated in the next section, both for the sake of the subject itself, and to introduce the formulation of the model in order to calculate the ratio of neutrino flux and gamma ray flux from AGN. This discussion yields the existence of a new mass scale at the knee energy, which is presented in the subsequent section. The computation of the neutrino flux and gamma ray flux follows.

III. THE HIGH ENERGY COSMIC RAY KNEE ENERGY

There is a break in the slope of the cosmic ray energy spectrum at around a few PeV ($=10^{15}$ eV). This value is called the knee energy. This phenomenon was explained as a change of expansion rate in the model[4]-[6]. The number of particles of type X with spin s emitted with energy E is given by

$$f_X(E) = \frac{2s+1}{2\pi^2} \int \eta_X(E/kT) \frac{E^2 V_S dt}{e^{E/kT - \mu/kT} \pm 1}, \quad (1)$$

where V_S is the effective volume around the surface of the system with temperature T that emits particles, $\eta_X(E/kT)$ is the emissivity and μ is the chemical potential. The \pm sign in the denominator is for fermions/bosons. It is reasonable to assume that the emissivity for black holes with a repulsive potential core is close to unity, since absorption is perfect for black holes and reflection is sure to follow from the repulsive force:

$$\eta_X(E/kT) \approx 1. \quad (2)$$

With the assumption

$$V_S = \frac{4\pi a}{(kT)^3} \quad (3)$$

and the expansion rate

$$t = bR^\alpha \quad (4)$$

and

$$R = \frac{d}{kT}, \quad (5)$$

where a , b and d are constants, one can compute the number of particles, $f_X(E)$, in Eq. (1),

$$f_X(E) = \frac{A_{X,\alpha}}{E^{\alpha+1}}, \quad (6)$$

where

$$A_{X,\alpha} = \frac{2(2s+1)ab\alpha d^\alpha}{\pi} \int_0^\infty \frac{x^{\alpha+2} dx}{e^{x-\mu_0} \pm 1} \quad (7)$$

and

$$\mu_0 = \mu/kT, \quad x = E/kT. \quad (8)$$

From the expansion rate in cosmology, the exponent α in Eq. (4) can be estimated as

$$\alpha = 2 \text{ at high temperature or radiation dominated era} \quad (9)$$

and

$$\alpha = 3/2 \text{ at low temperature or matter dominated era.} \quad (10)$$

For the latter, the exponent varies depending on the assumed mixture of radiation and matter. Note that all relativistic particles behave like radiation as far as the relationship between pressure and energy density is concerned. (i.e., $p = \rho/3$ for radiation as well as for relativistic particles.)

For high temperature or high energy ($\alpha = 2$), the energy spectrum behaves as

$$f_X(E) \approx 1/E^3 \quad (11)$$

and for low temperature or low energy ($\alpha = 1.5$), the energy spectrum behaves as

$$f_X(E) \approx 1/E^{2.5}. \quad (12)$$

This is consistent with the observed cosmic ray energy spectrum. It explains the existence of the knee energy in the cosmic energy spectrum. How about its magnitude? That is the subject of the next section.

IV. THE EXISTENCE OF A NEW MASS SCALE

At the knee energy of a few PeV or at the corresponding temperature, all particles of rest mass below the GeV or TeV scale are moving with relativistic speed, so they contribute as radiation-like or they give the relationship, $p = \rho/3$. Then, one cannot get a knee energy at the PeV scale in the model of this article. They would give a knee energy in their rest mass range. In order to create a knee energy in the cosmic ray spectrum at a few PeV, one has to assume the existence of particles of a few PeV

mass in black holes. Or equivalently there has to exist a mass scale that creates significant amounts of particles of a few PeV inside black holes, so that a significant departure from the radiation-like relationship, $p = \rho/3$, is established. This can be viewed as observational evidence for a new mass scale at a few Pev. It is, then, important to establish such a mass scale by other experimental observations.

An important question is what is the least massive particle at this new mass scale, so that it can be observed as a stable or at least a quasi-stable particle. Let us consider some possibilities.

A. The lowest mass is less than a few TeV. This particle can be produced at LHC. This is a lucky case for the LHC experimental groups. However, it is not clear whether one can produce a cosmic ray knee energy at the PeV range by unstable particles at these mass ranges.

B. The lowest mass is larger than a few TeV. This is an unlucky case for LHC. The Pierre Auger Project would be the only way to detect such particles. In the analysis of secondary shower particles, one can inquire whether various combinations of subsystems can make a bump at a particular mass value. That can be applied to a search for stable or unstable particles. One can make a search for masses with a fraction of a PeV for production in the atmosphere or up to the Pev mass scale for stable particles produced in black holes. These are conceivable for the Pierre Auger Project.

If any of the stable particles discussed above is weakly interacting, it becomes a candidate for dark matter. For a discussion of a PeV-scale supersymmetric theory, see e.g., reference[14].

If one gives a name for particles at this PeV mass scale, a designation based on the word for knee may be appropriate. If one uses a latin word, genu (or ginocchio for italian), it may become genon. Since this could be confused with a biological usage, one may call it simply kneeon[15].

V. RATIO OF NEUTRINO FLUX AND GAMMA RAY FLUX

The flux of gamma rays and neutrinos in this model can be written as ($\lambda = \alpha + 1$)

$$f_X(E) = \frac{A_{X,\lambda-1}}{E^\lambda} \quad (13)$$

where

$$A_{\gamma,\lambda-1} = \frac{2K_\lambda}{\pi} \int_0^\infty \frac{x^{\lambda+1}}{e^x - 1} dx \quad (14)$$

for gamma rays and

$$A_{\nu,\lambda-1} = \frac{3K_\lambda}{\pi} \int_0^\infty \frac{x^{\lambda+1}}{e^x + 1} dx \quad (15)$$

for neutrinos, where

$$K_\lambda = 2ab(\lambda - 1)d^{\lambda-1} \quad (16)$$

Here, the chemical potential for gamma rays is zero, and the same is assumed for mass zero neutrinos. Then, one gets

$$\frac{A_{\nu,\lambda-1}}{A_{\gamma,\lambda-1}} = \frac{3 \sum_{n=1}^{\infty} (-1)^n \frac{\Gamma(\lambda+2)}{n^{\lambda+2}}}{2 \sum_{n=1}^{\infty} \frac{\Gamma(\lambda+2)}{n^{\lambda+2}}} = \frac{3}{2} \left(1 - \frac{1}{2^{\lambda+1}}\right) \quad (17)$$

This ratio is given as

$$\frac{3}{2}(7/8, 0.912, 15/16) \quad \text{for } \lambda = (2, 2.5, 3) \quad (18)$$

Obviously, the factor 3 for the neutrino flux is for three kinds of neutrinos and the factor 2 for the gamma rays is for two polarizations. The three neutrinos have equal intensities and there is no oscillation when they propagate. The last statement is independent of the massless assumption for neutrinos.

It is also obvious that gamma rays and neutrinos should have the same spectral index and that both should have the same knee energy for each AGN. As the result of a new mass scale, the knee energy has an approximately universal value. Each AGN has different physical conditions for gravitational collapse and subsequent expansion and each can have different spectral index below the knee energy. However, a spectral index of 3 above the knee energy is most likely to be universal since it is caused by radiation domination. Below the knee energy, the spectral index is decided by the mixing of radiation-dominated component of light particles and a matter-dominated component of heavy particles. Thus, each AGN can have different spectral index, as seen in the gamma ray observations[1],[2]. More explicitly,

$$\text{for } p = \frac{\epsilon}{3}\rho, \quad (19)$$

with

$$0 \leq \epsilon \leq 1, \quad (20)$$

one gets

$$\alpha = \frac{3 + \epsilon}{2} \quad (21)$$

and

$$\lambda = \alpha + 1 = 2.5 + \epsilon/2. \quad (22)$$

If one includes the curvature term in the Friedman metric, one ends up with a more complicated form.

VI. DISCUSSION

The observation of a knee energy at a few PeV implies the existence of a new mass scale in nature in this model. It may be characteristic of the appearance of new physics, a conclusion already indicated from the observation of high energy cosmic rays with a knee energy.

It suggests to find such evidence from other experimental observation, most likely from a detailed analysis of the Pierre Auger Project data.

A further important point of this model is that the properties of black holes have been completely changed, a revolutionary change. The highest energy cosmic rays observed on Earth may be coming from black holes, an irony considering the classical description of black holes, which tells us that nothing comes out of them. The Hawking radiation emitted by massive black holes is miniscule, since the Hawking temperature is inversely proportional to the black hole mass. High energy gamma rays as well as high energy neutrinos are coming out of them, too.

Jets coming from AGN can be understood from this model. They are low energy components, which were accumulated by the magnetic field in the AGN.

In this modified form of black holes, a lot of stuff is coming out. As a result, the mass of a black hole can be reduced by the emission process. In the old picture, the mass of a black hole can only increase. This creates a new scenario for the development of AGN or black holes. The core of AGN can become smaller on a historical time scale. This may have something to do with the observational fact that large massive black holes in AGN are at larger distances or at a long gone past, while all galaxies in our neighborhood have core black holes with smaller masses at the center. One can postulate that an ordinary galaxy with a small central black hole can be a derivative of an AGN from the old days that has a massive black hole[16].

A black hole can become a neutron star by reducing mass by emission. If the remnant core of SN 87A is a black hole at the present time, it may become a neutron star at some later time. That is a possible scenario now.

Finally, I should point out the possibility of the formation of massive black holes made of dark matter. If they are surrounded by dark matter, then one does not observe them as visible AGN. In other words, they are invisible AGN. Then, such objects can emit particles, dark matter particles, gamma rays, neutrinos and possibly ordinary cosmic rays. They become sourceless cosmic rays as far as the optical signature is concerned. In such cases, the only signature is high energy gamma rays and neutrinos. A recent report on high energy cosmic rays in the northern hemisphere that are not correlated with known AGN[?] may be correlated with invisible AGN. One has to consider a correlation with gamma ray sources in such a case. One might ask why such a signature was observed in the northern hemisphere only so far. There is another observation data where a north-south asymmetry is observed[18].

Acknowledgments

The author would like to thank Jean Krisch, James Wells and David N. Williams for useful discussions.

-
- [1] Hartman, R.C. et al., ApJS 123, 79 (1999).
 - [2] Weeks, T. C., Tev Gamma-Rays Observations and the Origin of Cosmic Rays: I, ICRC 2007, pp. 3.
 - [3] The Pierre Auger Collaboration, Science 318, 938 (2007)
 - [4] Tomozawa, Y., Magnetic Monopoles, Cosmic Rays and Quantum Gravity, in the Proc. of 1985 INS International Symposium on Composite Models of Quarks and Leptons (Tokyo, edit. Terazawa, H. and Yasue, M., 1985), pp. 386.
 - [5] Tomozawa, Y., The Origins of Cosmic Rays and Quantum Effects of Gravity, in Quantum Field Theory (ed. Mancini, F., Ersever Science Publishers B. V., 1986) pp. 241. This book is the Proceedings of the International Symposium in honor of Hiroomi Umezawa held in Positano, Salerno, Italy, June 5-7, 1985.
 - [6] Tomozawa, Y., Cosmic Rays, Quantum Effects on Gravity and Gravitational Collapse, Lectures given at the Second Workshop on Fundamental Physics, University of Puerto Rico, Humacao, March 24-28, 1986. This lecture note can be retrieved from KEK Kiss NO 200035789 at http://www-lib.kek.jp/KISS/kiss_prepri.html
 - [7] Tomozawa, Y., Gravitational Waves, Supernova and Quantum Gravity, in Symmetry in Nature, (Scuola Normale Superiore, Pisa, 1989) pp. 779, Section 2 and 3.
 - [8] Tomozawa, Y., Exact Solution of the Quantum Einstein Equation and the Nature of Singularity, in the Proc. 5th Marcel Grossman Meeting on General Relativity (ed. D. Blair et al., Perth, Australia, 1988) pp. 527.
 - [9] Tomozawa, Y., Black Hole Oscillation, in the Proc. 5th Marcel Grossman Meeting on General Relativity (ed. D. Blair et al., Perth, Australia, 1988) pp. 629.
 - [10] Majumdar, A. and Tomozawa, Y., Progr. Theoret. Phys. (Kyoto) 82, 555 (1989).
 - [11] Majumdar, A. and Tomozawa, Y., Nuovo Cimento 197B, 923 (1992).
 - [12] Tomozawa, Y., Astron. Astrophys. Suppl. Ser. 97, 117 (1993).
 - [13] Hawking, S., <http://www.newscientist.com/article/dn6151.html>.
 - [14] Wells, J., Phys. Rev D71, 015013 (2005).
 - [15] If one objects to the use of this terminology because of the proximity of its pronunciation to that of the 10 th atom, Neon, one may use sion or xion from the Chinese word for knee, xi, (pronounced si), and the Japanese, sitsu, or hizon from the Japanese word for knee, hiza. (Japanese words have a double structure, one from a Chinese derivative and the other from Japanese proper.)
 - [16] Tomozawa, Y., Mass and Distance Scale of Black Holes in Quasars and Active Galactic Nuclei, in Active Galactic Nuclei (ed. Miller, H. R. and Wiita, P. J., Springer Verlag, 1988) pp. 236.
 - [17] Abbasi, R. U. et al., <http://arXiv.org/abs/astro-ph/0703099>.
 - [18] Tomozawa, Y., Mod. Phys. Lett. A 22, 1553 (2007).